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by Ben F. McCreary

Manned Spacecraft Center
Houston, Texas

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SEPARATION TRAJECTORY CHARACTERISTICS

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SUMMARY

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A parametric study was made of separation trajectory characteristics resulting when one vehicle separates from another in near-earth orbits. The separation trajectory parameters presented in this report apply to eccentric orbits with perigees of 87 nautical miles (n. mi.) and apogees up to 161 n. mi. with circular orbits up to 150 n. mi. Ballistic numbers of the active vehicle were varied between 15 and 60 lb/ft^2 and separation velocities of up to 50 ft/sec were considered. Proper selection of the separation parameters allows the two vehicles to be placed in any relative position desired. A posigrade separation will place the active vehicle behind the reference vehicle, and for certain ballistic numbers, the active vehicle will reverse position and go ahead of the other. A retrograde separation will always place the active vehicle in front of the reference vehicle, and radial separation will return the two vehicles to positions near each other in each succeeding orbit.

Author

INTRODUCTION

During Project Mercury, a small sphere with a flashing light was ejected from the spacecraft and placed in a separate orbit. This test evaluated visual observations up to 15 n. mi. Subsequent testing planned for the Gemini program will involve the use of other orbiting vehicles external to the manned spacecraft. Astronaut training in visual observation, evaluation of the Gemini onboard radar and computer by a separate orbiting radar beacon, and preliminary training in rendezvous and docking maneuvers using the orbiting beacon are some of the projects now planned that involve two separated vehicles in near-earth orbit. This same type of testing will also be applicable to other space experiments such as space station-ferry vehicle operations. Experience gained during Mercury and Gemini will be useful in the Apollo mission for the rendezvous and docking of the lunar excursion module with the command and service modules.

Other studies involving more than one orbiting vehicle are listed in references 1 to 4; however, there appears to be a lack of data in the area of the relative separation of two orbiting vehicles. This report presents the results

of a parametric investigation and describes how ballistic number, separation velocity, and separation angle can be varied to place two vehicles at virtually any relative position desired. This study originated in support of the previously mentioned Project Mercury test and future Gemini missions. The results of these tests can be extended and generalized to be applicable to most near-earth orbital programs. Since this report is presented from an application standpoint, no details will be given concerning the development of the equations of motion or the technique of computation. This report is confined to three orbits, with the basic results derived from two vehicles in elliptical coplanar orbits. The appendix presents a detailed report of the application of the results of this study to the Project Mercury test.

SYMBOLS

A surface area, sq ft

N_B ballistic number, W/C_DA, lb/ft^2

C_D drag coefficient

R range, separation distance between two vehicles, n. mi.

ΔV separation velocity, ft/sec

W weight, lb

β separation angle referenced to local horizontal, deg

METHODS OF VEHICLE SEPARATION

An active vehicle separated from a reference vehicle along the velocity vector will achieve the greatest range for a given separation velocity. A posigrade separation will allow an active vehicle to go behind the other vehicle; a retrograde separation will allow it to go in front of the other vehicle. An angular separation reduces the effective separation velocity along the velocity vector, which, in turn, reduces the separation range for given separation velocities. If the angular separation reaches $\pm 90^\circ$, there will be no change along the velocity vector, and a radial separation will occur, placing each vehicle in equal period orbits. A positive separation will produce an orbit with the active vehicle behind the reference vehicle; a negative separation produces an orbit with the active vehicle in front. This type of separation is desirable for repeated observations.

RESTRICTIONS

This report is confined to three orbits, and the basic results are derived from two vehicles in elliptical coplanar orbits with perigee and apogee at 87 and 147 n. mi., respectively.

The apogee was arbitrarily selected as the point for initially separating the two vehicles; however, data are presented which enable apogee separation results to determine other orbital separation point results. Generalizations are made that will allow these results to be used for other near-earth elliptical and circular orbits.

The data for this study were obtained by varying the parameters of the ballistic number, the separation velocity, the separation angle, and the orbital separation points.

Results presented in this study are based on a reference vehicle ballistic number of 45 lb/ft^2 and an active vehicle ballistic number between 15 and 60 lb/ft^2; therefore, the ratio of the ballistic numbers of the two vehicles is between 3:1 and 0.75:1. These ratios will not give the same trajectory results if another reference vehicle ballistic number is used within the eccentric orbits considered in this report. To maintain these ratio limits, an increase in ballistic number would necessitate an increase in the mass of each vehicle and would lengthen the orbit lifetime. Separation distances would then increase, and the range within the ratio limits would converge. A composite atmosphere density and pressure table based on the Patrick Reference Atmosphere, the ARDC Model Atmosphere 1959, and an atmosphere derived from the Discoverer series satellites was used for this study. This atmosphere is called the Mercury Atmospheric Model.

RESULTS AND DISCUSSION

Vehicle Separation Method

Along velocity vector.- When an active vehicle is separated in the posigrade direction, it will initially go ahead of the reference vehicle. The separation ΔV increases the period of the active vehicle, and the two orbits begin to diverge. As this occurs, the active vehicle will always pass over the other and remain behind, if the ballistic numbers of the two vehicles are reasonably the same.

If the ballistic number of the active vehicle is below that of the other vehicle, the orbit of the active vehicle will decay more rapidly. When this occurs, the active vehicle will pass under the reference vehicle and remain ahead throughout the flight. If, for a given case, the ballistic number of the active vehicle causes a more rapid decay rate than desired, the effect can be overcome by increasing the separation velocity, thereby increasing the

period of the active vehicle. Typical posigrade separations are shown in figure 1. Separation velocity effects are shown in part (a), ballistic number effects are shown in part (b), and separation angles in part (c).

If the active vehicle is separated in a retrograde direction, it will initially go behind the other. After a short time, the orbit of the active vehicle will begin a more rapid decay rate, and the vehicle will pass under the reference vehicle and remain ahead throughout the flight. If this decay rate is too rapid, the trajectory of the active vehicle will be terminated by reentry. Typical trajectories for retrograde separations are shown in figure 2. Effects of separation velocity are shown in part (a), ballistic number in part (b), and separation angles in part (c).

Angular separations.- Angular separations have essentially the same characteristics as both the posigrade and retrograde separations mentioned previously. The separation ΔV, however, has a vertical component which reduces the effective separation ΔV by the cosine of the separation angle. This reduces the separation parameters by approximately the same ratio as those obtained with no angular separation. Separation range can be approximated by

$$R_{\beta} = R_{\beta=0} \cos \beta \tag{1}$$

where

$$\beta = \pm 90$$

For the retrograde separation $R_{\beta=0}$ must become $R_{\beta=180}$ and the angular separation must be measured from 180°.

Radial separation.- Radial separations result in equal period orbits. Maximum range will be obtained at the $\frac{1}{2}$-period point on each orbit. Maximum altitude occurs at the $\frac{1}{4}$- and $\frac{3}{4}$-period points and is ±25 percent of the maximum range. Range and altitude have a linear variation with separation velocity and conform to a slope of 2. A negative radial separation (towards earth center) will reduce the flight-path angle and cause the active vehicle to go below and ahead of the other vehicle and return in an elliptic pattern. A positive radial separation will increase the flight-path angle and cause the active vehicle to go above and behind the other vehicle and return in an elliptic pattern.

Effect of Considered Variables

Ballistic number and separation velocity.- Ballistic number effects on range at the end of each pass (longitude where initial separation occurred) are shown in figure 3 for specific posigrade separation velocities. These effects are not universally proportional because results with lower ballistic numbers, combined with lower separation velocities (less than 2 ft/sec), tend to decay in orbit rather quickly after the first pass. This can be seen in figure 3 as the separation velocity curves below 5 ft/sec pass through the 0 point, denoting that the active vehicle has gone ahead of the other. However, ballistic numbers

above 30 lb/ft^2, combined with separation velocities greater than 1 ft/sec, or all ballistic numbers combined with separation velocities greater than 5 ft/sec, place the active vehicle into an orbit which would be large enough to cause the active vehicle to remain behind the other vehicle for three orbits. Under these conditions, the range is proportional to separation velocity, and ranges for other separation velocities can be interpolated within a reasonable accuracy.

Range determination as a function of ballistic number and separation velocity is shown in figure 4. The curve width is the envelope of ballistic numbers between 15 and 60 lb/ft^2. Separation velocity effects for the first and second passes are reasonably linear. Convergence of the envelopes at higher separation velocities on the second and third passes is the result of these velocities trying to nullify the differences in the two orbits caused by mismatching the ballistic numbers of the vehicles.

The effects of ballistic number and retrograde separation velocity on range are shown in figures 5 and 6. Care must be exercised in selecting the appropriate separation velocity and ballistic number, or reentry will occur during the second or third orbit. Separation velocities below 30 ft/sec will not cause reentry within the three-orbit study, but those above 30 ft/sec have a great reentry probability after the first orbit. This cannot be effectively decreased by increasing the ballistic number of the active vehicle. Reentry will probably occur after the first orbit if $\Delta V = 50$ ft/sec and $N_B =$ 15 lb/ft^2. In the third orbit, reentry will probably occur for all ballistic numbers when $\Delta V = 50$ ft/sec, and for ballistic numbers below 19 lb/ft^2 when $\Delta V = 40$ ft/sec. By combining lower ballistic numbers with higher retrograde separation velocities, orbit decay is increased considerably. Reentry boundaries do not mean that reentry occurs at that point, but that reentry will terminate the trajectory before the subsequent pass.

Separation angle.- Within the restriction of the report, the range accuracy using equation (1) is 92 percent.

When a vehicle is separated radially, equal period orbits will result if the ballistic numbers are matched. The range will have a linear variation with separation velocity as shown in figure 7. If the ballistic number of the active vehicle is greater than the ballistic number of the reference vehicle, the period is increased, placing the active vehicle behind the other. Conversely, when the ballistic number of the active vehicle is below the ballistic number of the reference vehicle, the active vehicle is placed in front. For unmatched ballistic numbers, figure 8 shows that the trajectories will be different for $\pm 90^\circ$ separations, but they will return to the same point at the end of passes 1 and 2, and almost the same point at pass 3.

Relative Velocities After Separation

The maximum velocity attained after a posigrade separation is dependent on vehicle separation velocity only. This is a diverging velocity (increasing

separation velocity) and will maintain about the same value in each orbit as seen in figure 9. These velocities occur at the $\frac{1}{2}$-period points.

During each subsequent pass after separation, the velocity slows down, and a converging velocity (decreasing separation velocity) results for a short time. The trajectory appears to loop, as seen in figure 1, and the active vehicle comes toward the reference vehicle for a short time. The size of the loop, or magnitude of the converging velocity, is primarily a function of ballistic number. Effects of separation velocity on converging velocity are shown in figure 10. Although this figure shows an increase in converging velocity with higher separation velocities, figure 11 shows that higher ballistic numbers reduce the converging velocity. This can be seen in figure 1 by each loop becoming tighter as the ballistic number increases.

Relative velocities for angular separations may be approximated within a reasonable degree of accuracy by using the equation (1) and substituting velocity V_β in the place of R_β, giving

$$V_\beta = V_{\beta=0} \cos \beta \tag{2}$$

When a vehicle is separated in a retrograde direction, it is not always confined to a definite pattern, as is the case in a posigrade separation. (See fig. 2(b).) There is no specific converging velocity increase with separation velocity. A high separation velocity can nullify any converging velocity, and the active vehicle will begin a diverging rate. A small separation velocity accompanied by a reasonable ballistic number can have a small converging rate as seen in figures 12 and 13. Velocity approximation cannot be made for diverging velocities resulting from angular retrograde separations. Diverging velocities obtained by a retrograde separation will be much higher and will not follow a cosine function decrease.

Application of Separation at Apogee to Other Separation Points and Orbits

Other separation points.- At apogee and perigee the flight-path angle is essentially 0°, and the separation velocity is maximum in the horizontal direction. Between apogee and perigee the flight-path angle is not 0°, and the separation velocity contains a vertical component. Ranges for a perigee separation can be obtained with the percentage curves in figures 14 and 15 by multiplying the apogee ranges by the values from the appropriate curve. Ranges for a separation between apogee and perigee are obtained by using the appropriate curve in figures 16 and 17. Apogee and perigee separations allow more compatible separation distances than those obtained by separating between apogee and perigee.

Larger eccentric orbits.- Separation velocities which add some ΔV up to 50 ft/sec to the inertial velocity will give essentially the same range and velocity values for orbits with apogee up to 161 n. mi. and perigee at 87 n. mi.

Figures 3 and 4 and 9 to 11 can be used with no adjustment. A retrograde separation for the same orbit will have smaller separation parameters by about 7 percent of those shown in figures 5, 6, 12, and 13.

Circular orbit.- Separation parameters are dependent on separation velocity only for vehicles separated in a 150-n. mi. circular orbit. Ballistic numbers in this report for 150-n. mi. circular orbits have no effect for three orbits. Posigrade and retrograde separation velocities give the same ranges, and reentry problems do not exist within the restrictions of this study. Although the magnitude of separation distances are the same, posigrade separations place the active vehicle above and behind the reference vehicle, and retrograde separations place it below and ahead of the other.

Separation ranges for circular orbits are about 4 percent greater than those in figures 3 and 4 with $N_B = 45$ lb/ft^2.

CONCLUDING REMARKS

As a result of the separation characteristic study discussed in this report, the following conclusions may be reached:

1. An active vehicle separated with a posigrade velocity will always go behind and above the reference vehicle. If the separation velocity is low enough and the ballistic number is less than that of the reference vehicle, drag differences will cause the active vehicle to go ahead of the other vehicle after the first orbit.

2. An active vehicle separated in a retrograde direction will always go below and in front of the reference vehicle and remain in that position, unless reentry terminates the trajectory within three orbits. Trajectories for a retrograde separation are not confined to a consistent pattern as are trajectories for a posigrade separation.

3. Range is reasonably proportional to separation velocity, and an approximation of range for angular separations can be obtained by the equation $R_\beta = R_{\beta=0} \cos \beta$, where R is the separation distance between two vehicles and β is the separation angle referenced to the local horizontal. This equation can be used for all separation angles except radial and near radial. The overall accuracy of the approximation is 92 percent.

4. Vehicles separated radially with matched ballistic numbers are placed in equal-period orbits. A positive radial separation will take the active vehicle above and behind the other vehicle, and a negative radial separation will take it below and in front of the other. If the ballistic number of the active vehicle is greater than that of the reference vehicle, the active vehicle will return to a point behind the other, and conversely, if the ballistic number of the active vehicle is below the ballistic number of the other vehicle, the active vehicle is placed in front.

5. Posigrade separation will result in large diverging velocities at the $\frac{1}{2}$-period point, and generally, small converging velocities at the end of each period. Velocities obtained from a retrograde separation are not confined to as specific a pattern.

6. Care must be exercised in selecting the appropriate retrograde separation velocity and ballistic number, or reentry will occur during the second or third orbit.

7. Apogee and perigee separation allow more compatible separation distances than those obtained by separating between apogee and perigee.

Manned Spacecraft Center
National Aeronautics and Space Administration
Houston, Texas, August 12, 1965

APPENDIX

MERCURY PROGRAM FLASHING LIGHT EXPERIMENT

The study for this report began in support of an experiment planned for the Mercury Program. An instrument package containing a flashing light was deployed to help gain information on an astronaut's ability to observe other objects in space under controlled conditions. The experiment required repeated observations for several orbits with a minimum range of 1 n. mi. and a maximum range of 15 n. mi. Ballistic numbers of the instrument package and the spacecraft were 28.21 and 45 lb/ft^2, respectively, and the design separation velocity of the package ejection spring was 10 ft/sec.

A radial separation would produce the type of orbit for repeated observations; therefore, -90° was chosen because the ballistic number of the package was less than that of the spacecraft, and it was desirable to have the package go below and ahead of the spacecraft. The radial separation was adequate, but it did not allow enough separation on the first pass for a $\pm 2^\circ$ system tolerance on the separation angle. A near radial angle of -92° satisfied the requirements by placing the instrument package in an orbit with minimum ranges between 2 and 12 n. mi. and maximum ranges between 6 and 15 n. mi. Figures 18 to 21 show the curves designed for this experiment. Figure 18 shows the effect of the ejection angle on the minimum and maximum ranges of the package. The ejection spring had a ± 5 percent tolerance on the ΔV capability. Figure 19 shows the effect of this tolerance combined with the ejection angle on minimum and maximum range. The relative position of the package is presented in figure 20. This figure is similar to the -90° separation shown in figure 8(b); the time history of the elevation angle and the range is presented in figure 21.

This experiment was conducted during the third through fifth orbits of the fourth manned orbital flight in May 1963. The results were successful, and the astronaut was able to observe the flashing light at the predicted ranges. (See ref. 4.)

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3. Knollman, G. C.; and Pyron, B. O.: Relative Trajectories of Objects Ejected From a Near Satellite. AIAA Journal, vol. 1, no. 2, Feb. 1963, pp. 424-429.

4. Staff of Manned Spacecraft Center: Project Mercury Summary Including the Results of the Fourth Manned Orbital Flight, May 15 and 16, 1963. NASA SP-45, Supt. Doc., U. S. Government Printing Office, Washington, D. C., 1963, pp. 218-220, 355.

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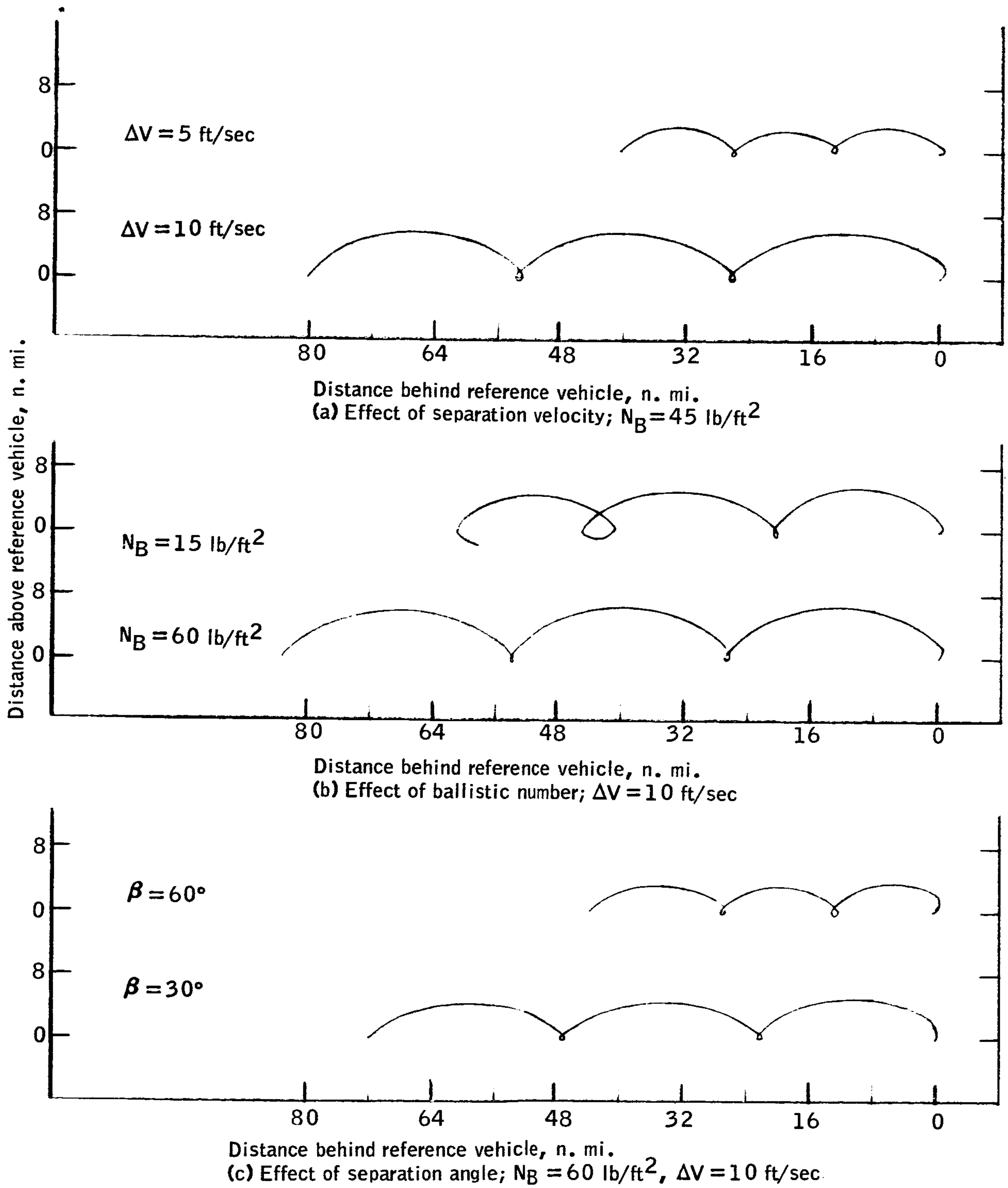

Figure 1.- Typical effect of posigrade ΔV, ballistic number, and separation angle on the separation distance of two objects.

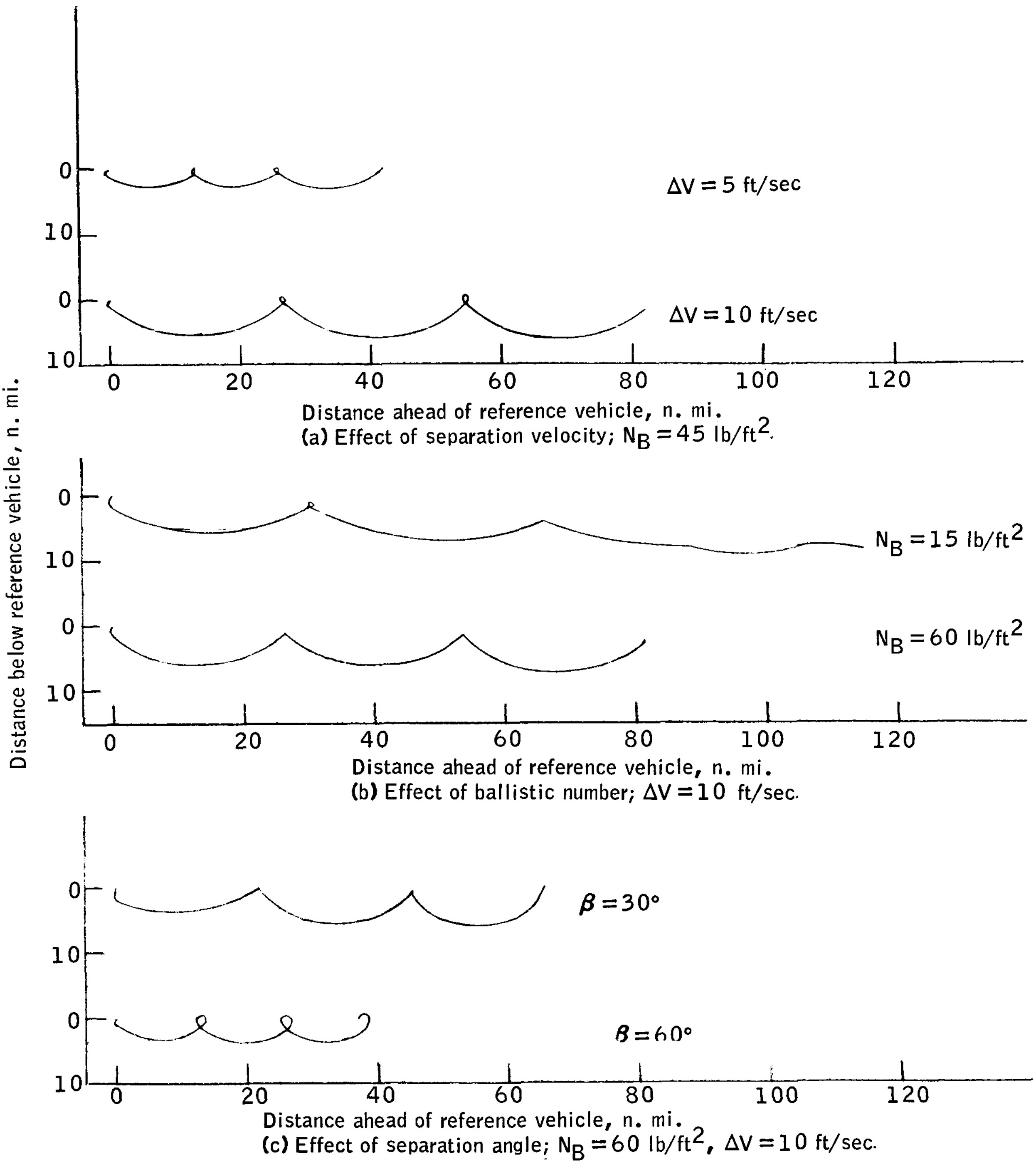

Figure 2.- Typical effect of retrograde ΔV, ballistic number, and separation angle on the separation distance of two objects.

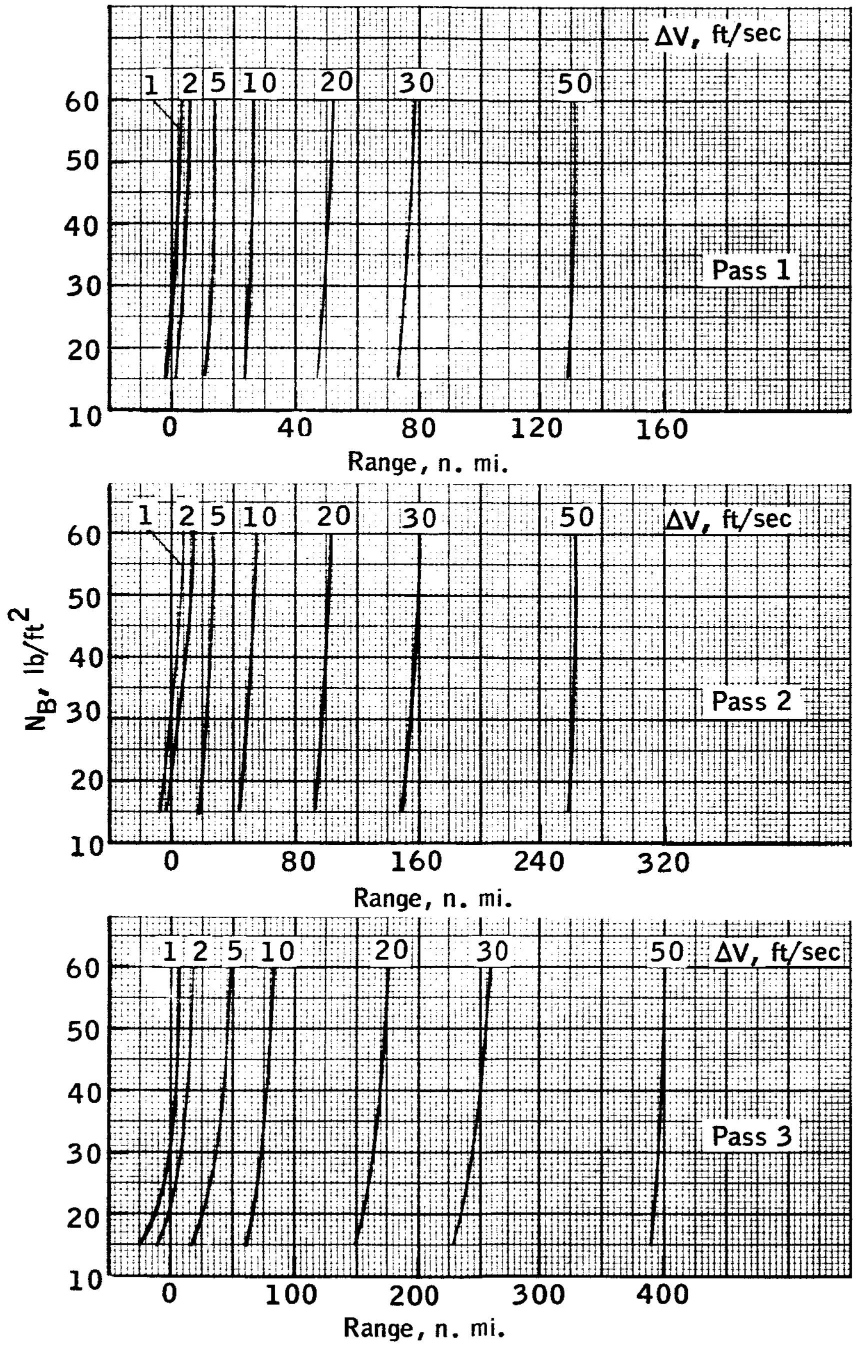

Figure 3. - Effect of ballistic number on range for specific posigrade values of ΔV along the velocity vector.

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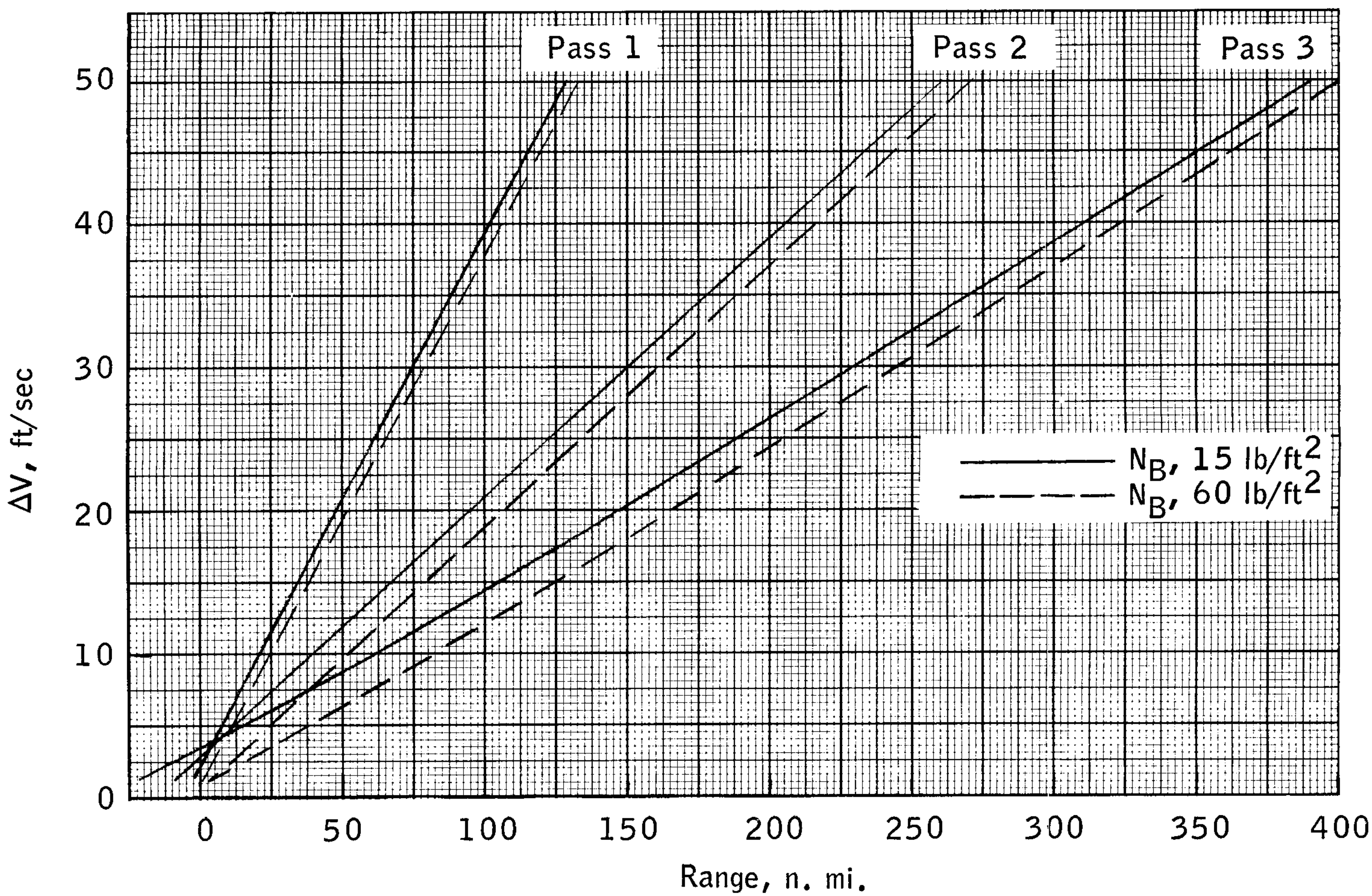

Figure 4.- Range as a function of ΔV values from 1 to 50 ft/sec for specific ballistic numbers and orbital passes.

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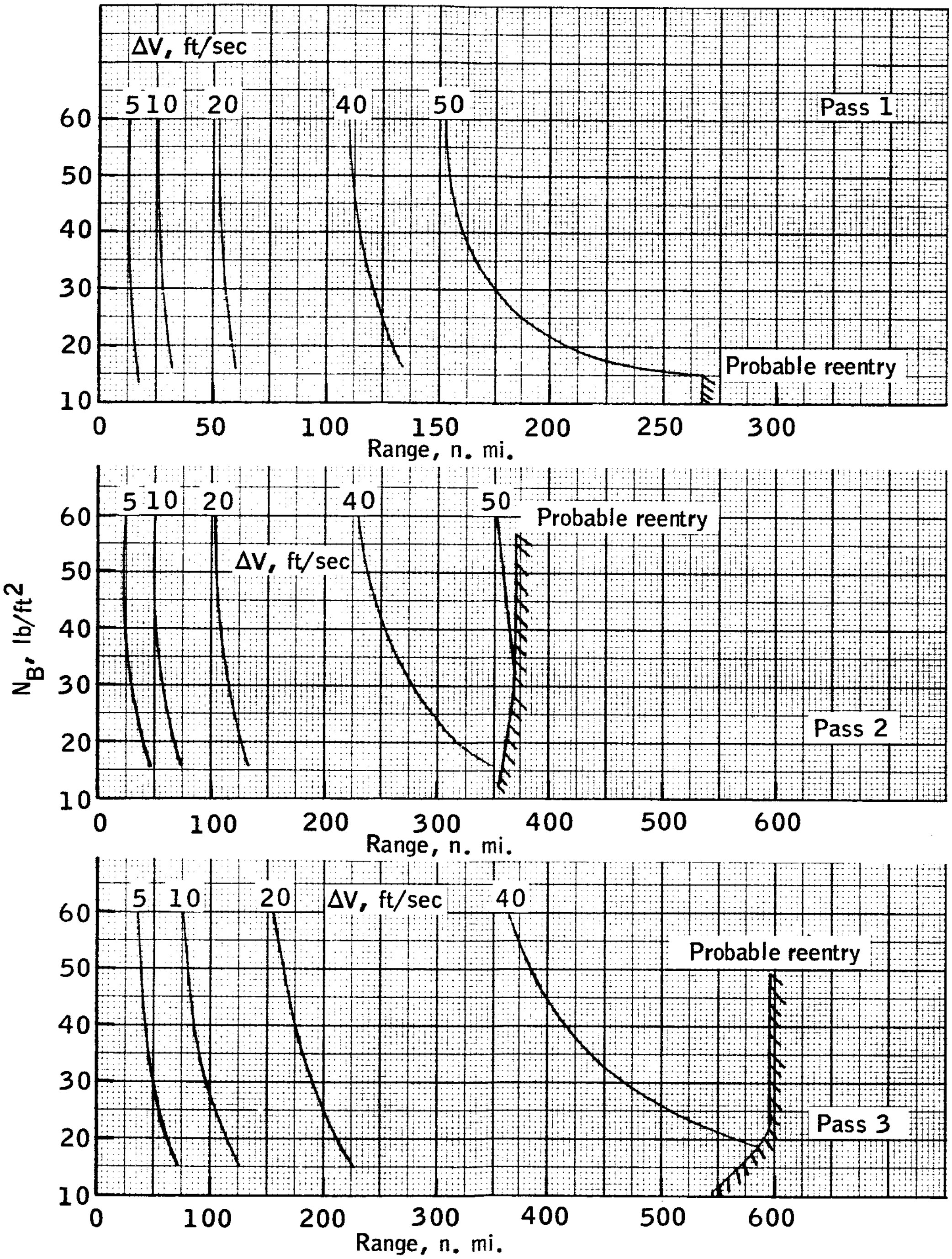

Figure 5. - Effect of ballistic number on range for specific retrograde values of ΔV along the velocity vector.

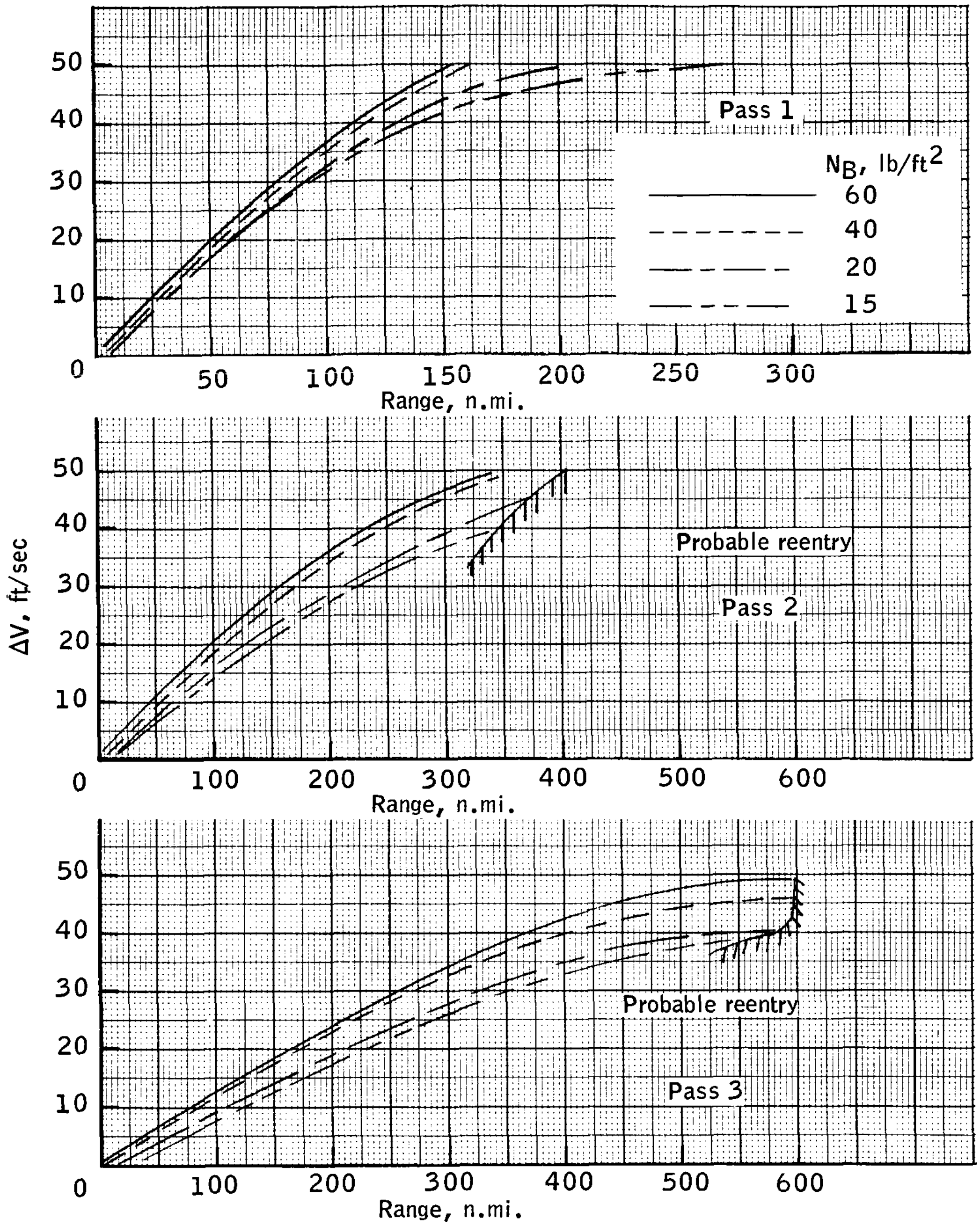

Figure 6. - Range as a function of retrograde ΔV along the velocity vector for specific ballistic numbers and orbit passes.

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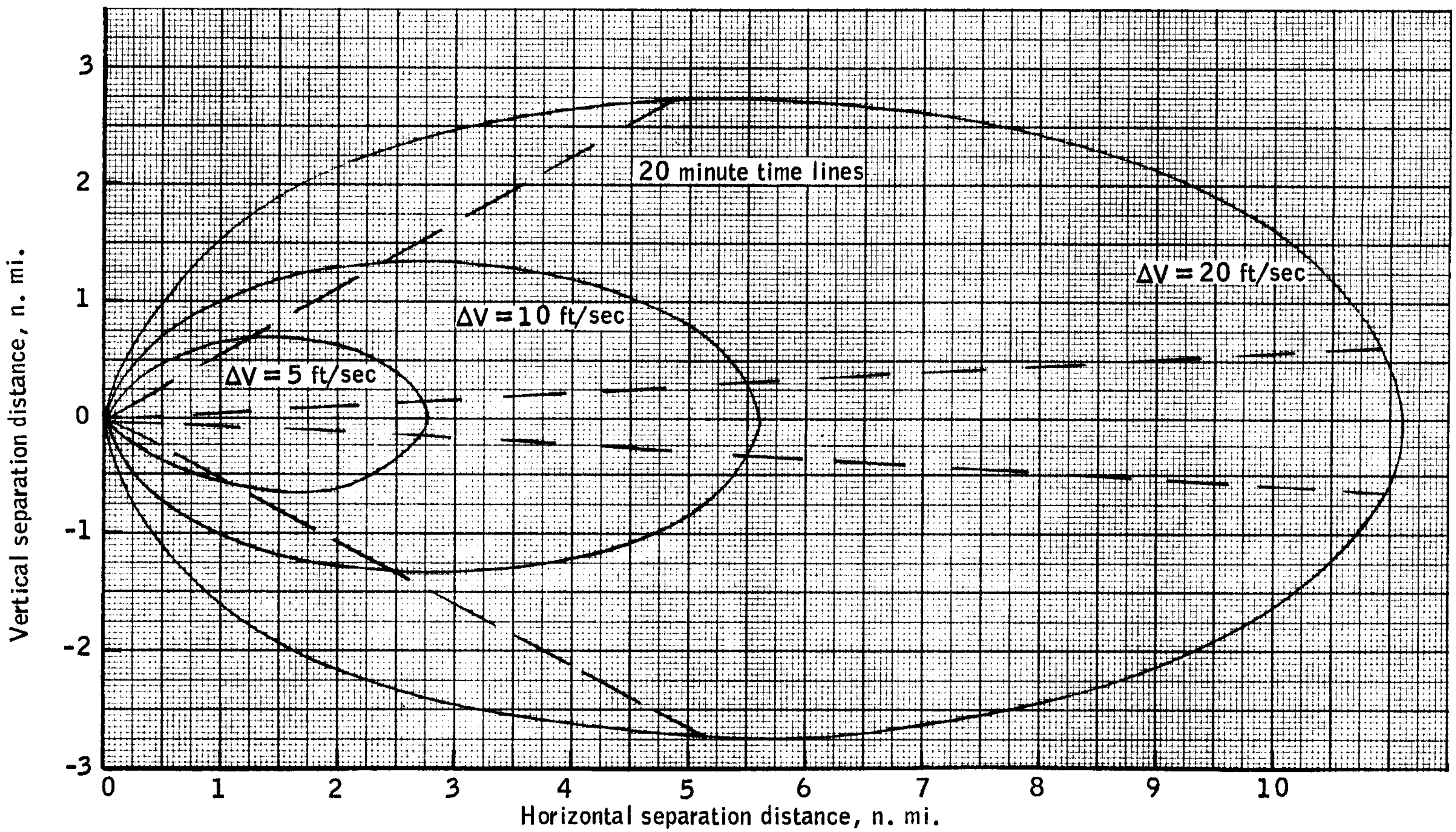

Figure 7. - Vertical and horizontal separation characteristics of equal period orbits for specific values of ΔV; $N_B = 45$ lb/ft^2.

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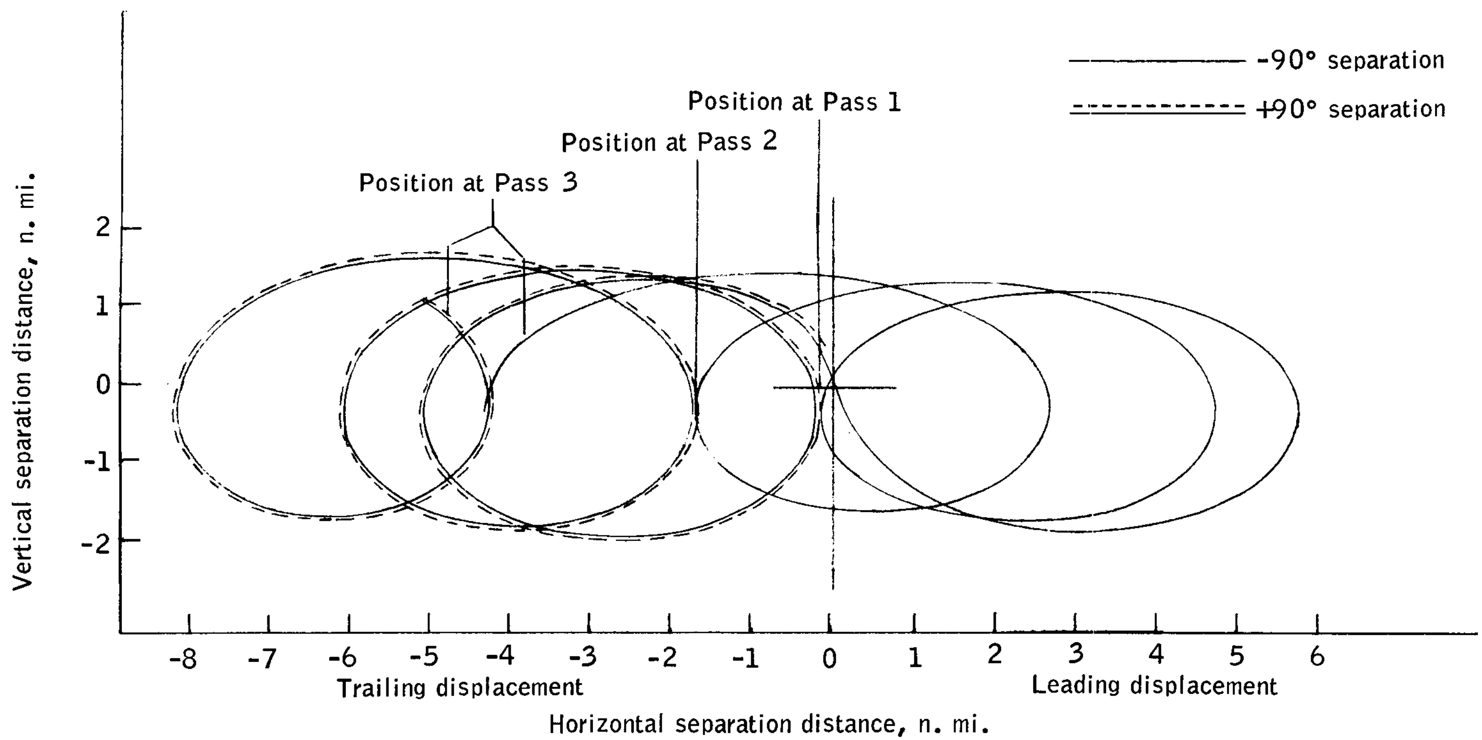

(a) $N_B = 67.5$ lb/ft^2

Figure 8.- Vertical and horizontal separation characteristics of equal period orbits for specific ballistic number. $\Delta V = 10$ ft/sec.

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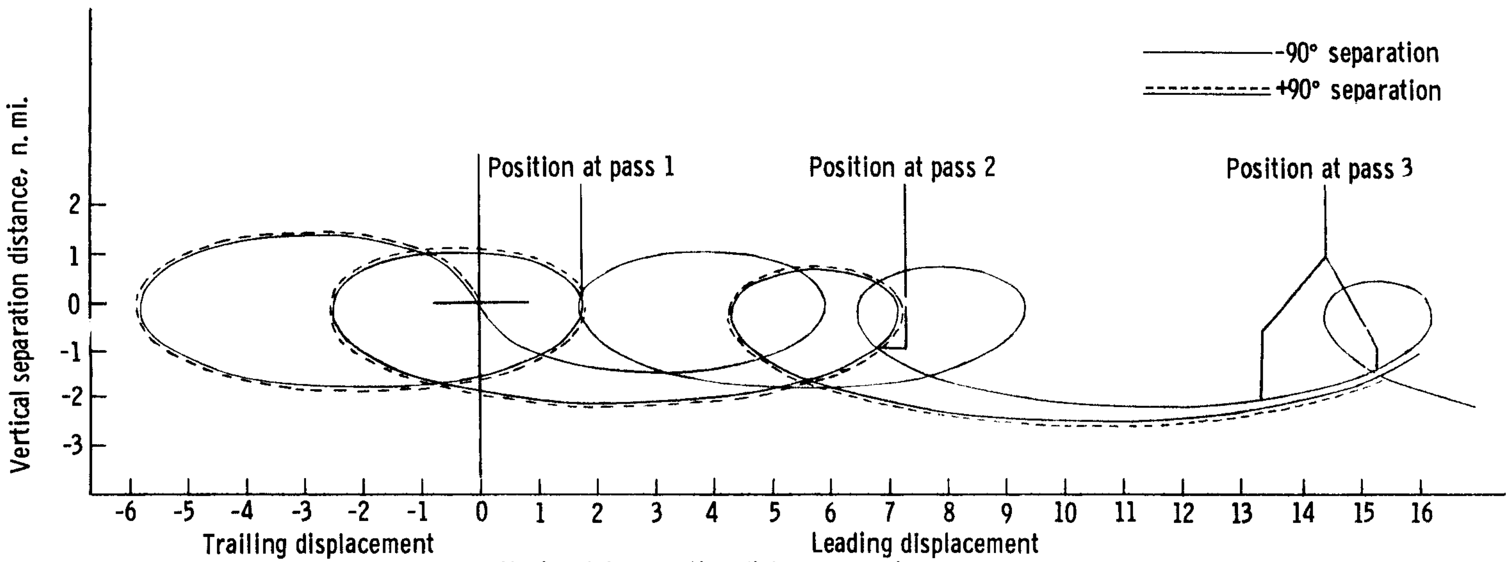

(b) $N_B = 22.5$ lb/ft^2

Figure 8. - Concluded.

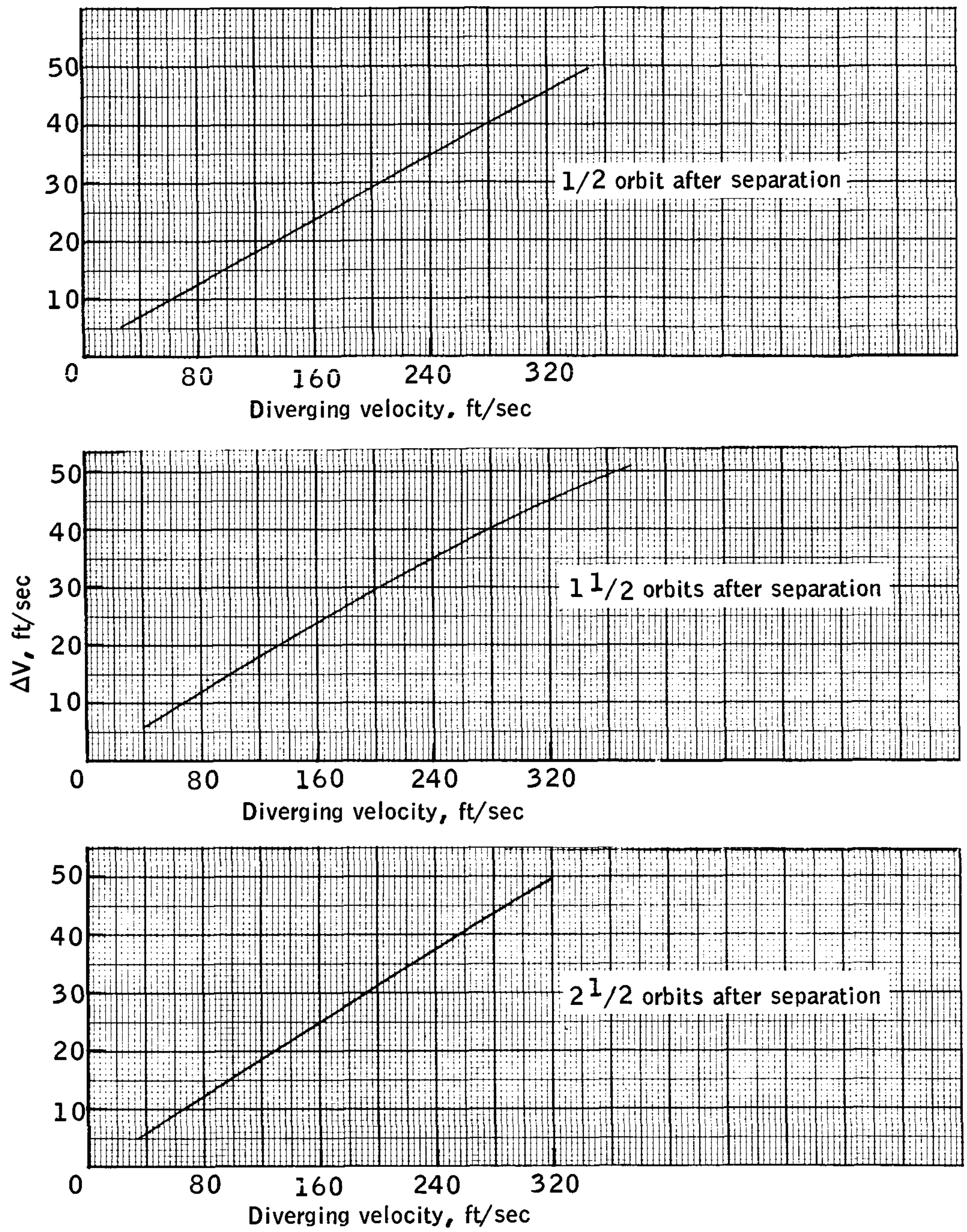

Figure 9. - Diverging velocity as a function of posigrade ΔV along the velocity vector for specific orbits after separation. All values of N_B apply.

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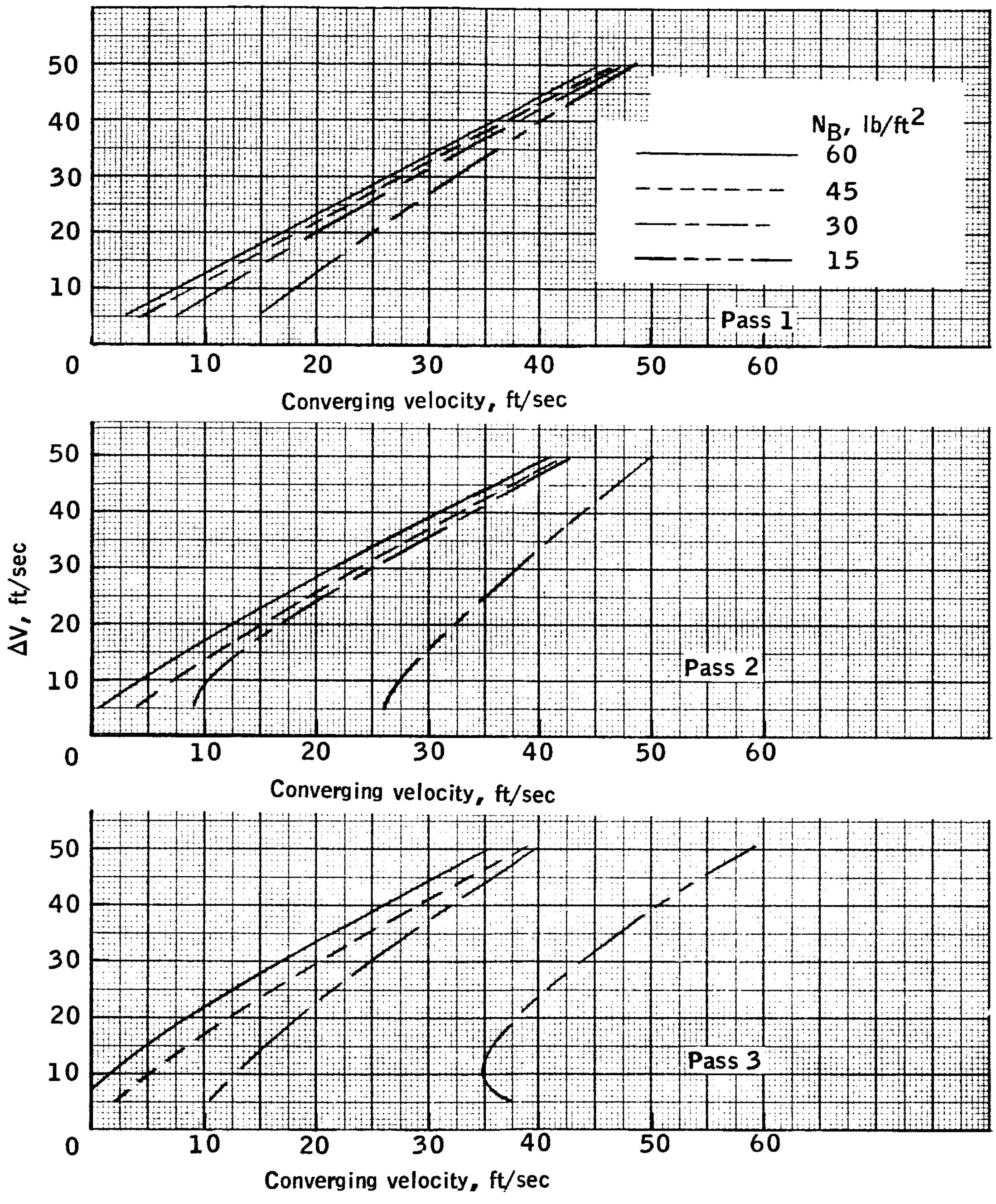

Figure 10.- Converging velocity as a function of posigrade ΔV along the velocity vector for specific ballistic numbers and orbit passes.

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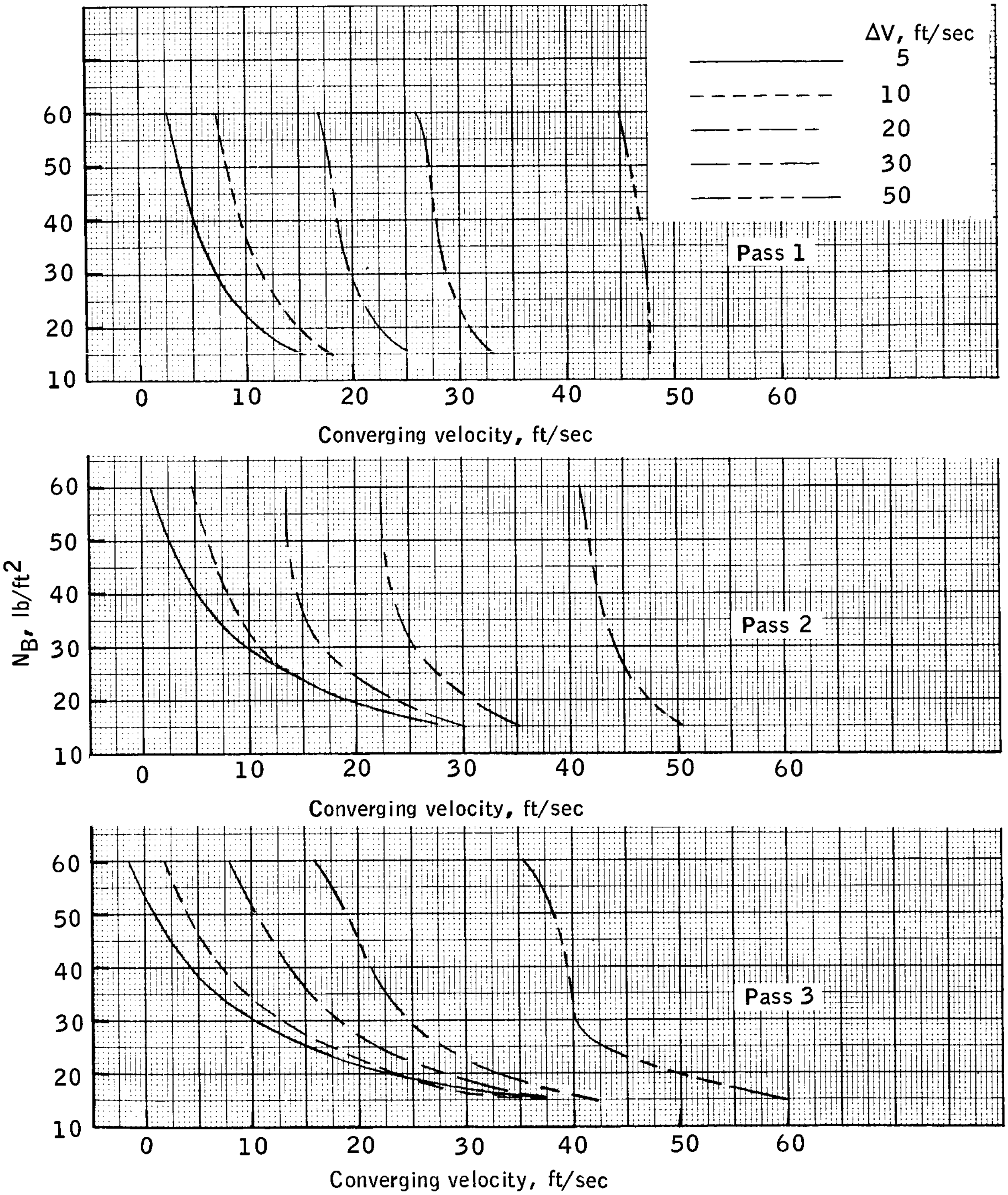

Figure 11. - Effects of ballistic number on converging velocity for specific posigrade values of ΔV, along the velocity vector.

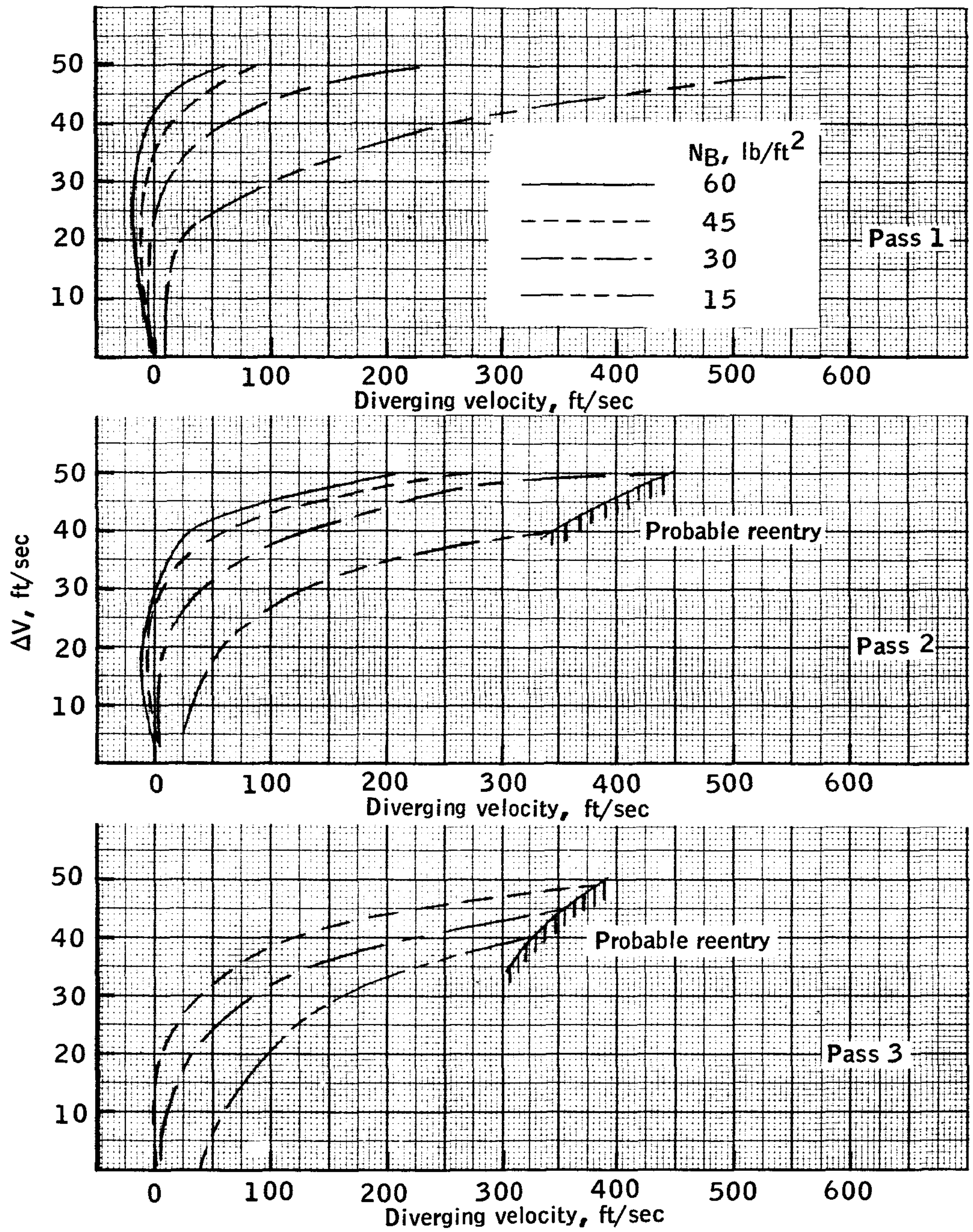

Figure 12.- Diverging velocity as a function of retrograde ΔV along the velocity vector for specific ballistic numbers and orbital passes.

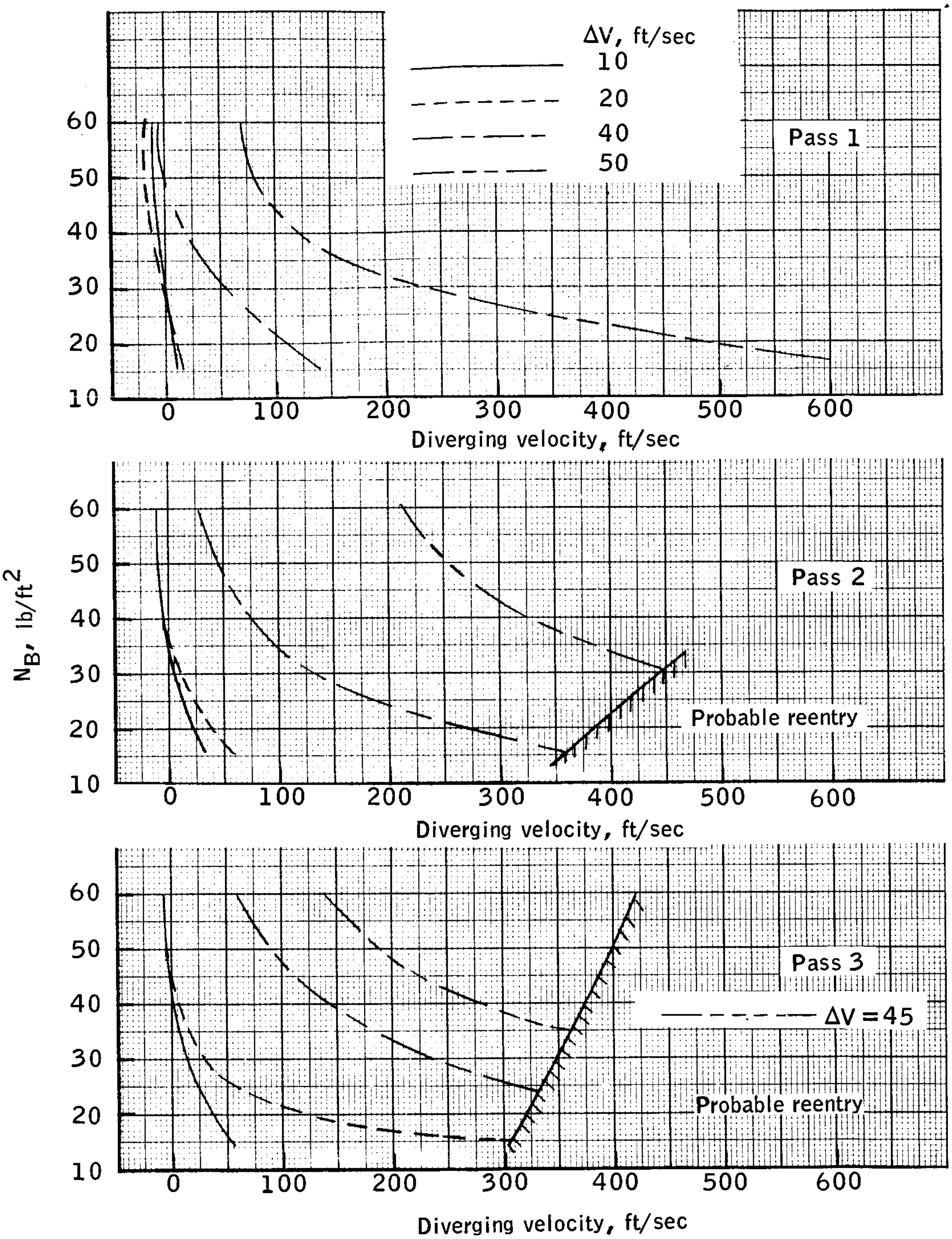

Figure 13. - Effect of ballistic number on diverging velocity for specific retrograde values of ΔV along the velocity vector.

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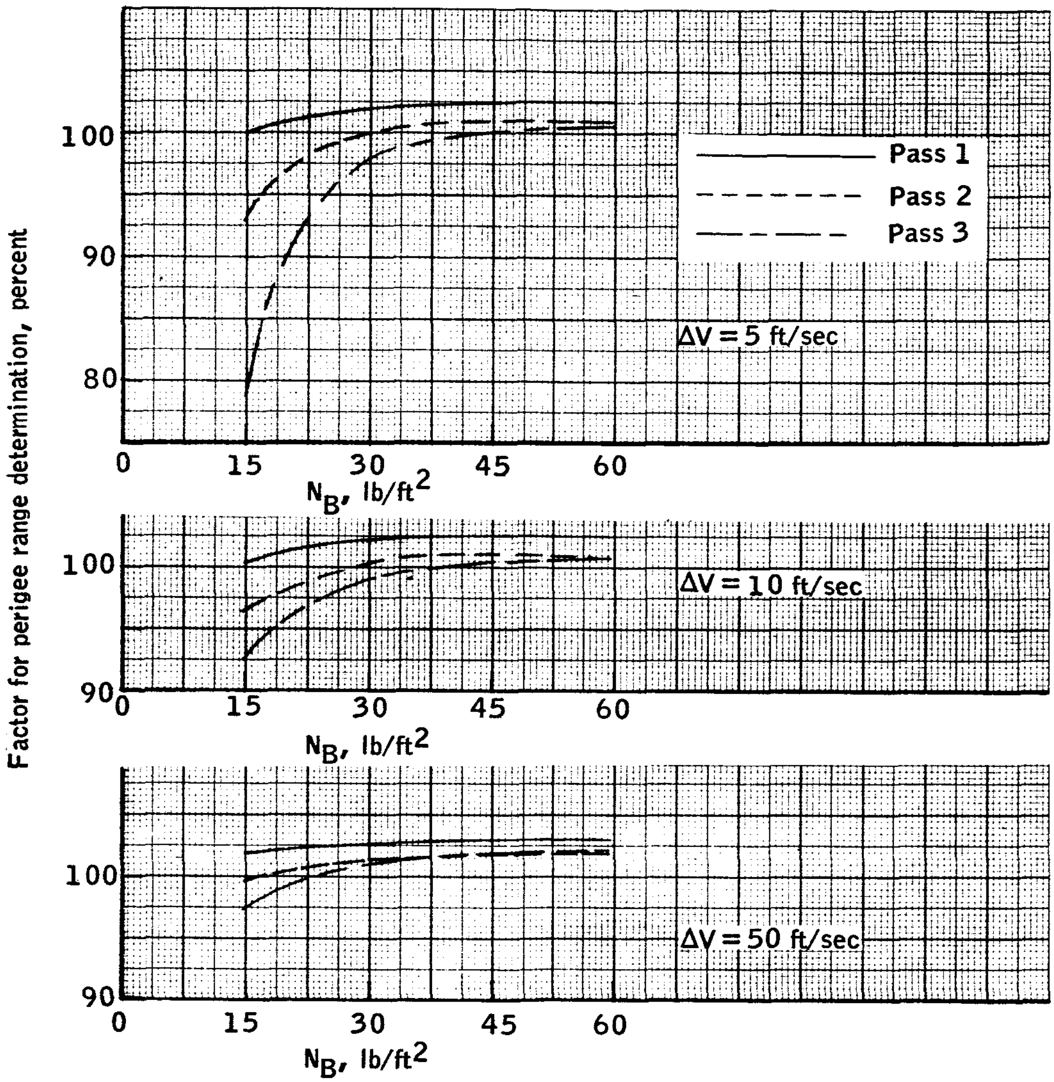

Figure 14. - Factor for perigee range determination as a function of ballistic number for specific values of ΔV and orbital passes.

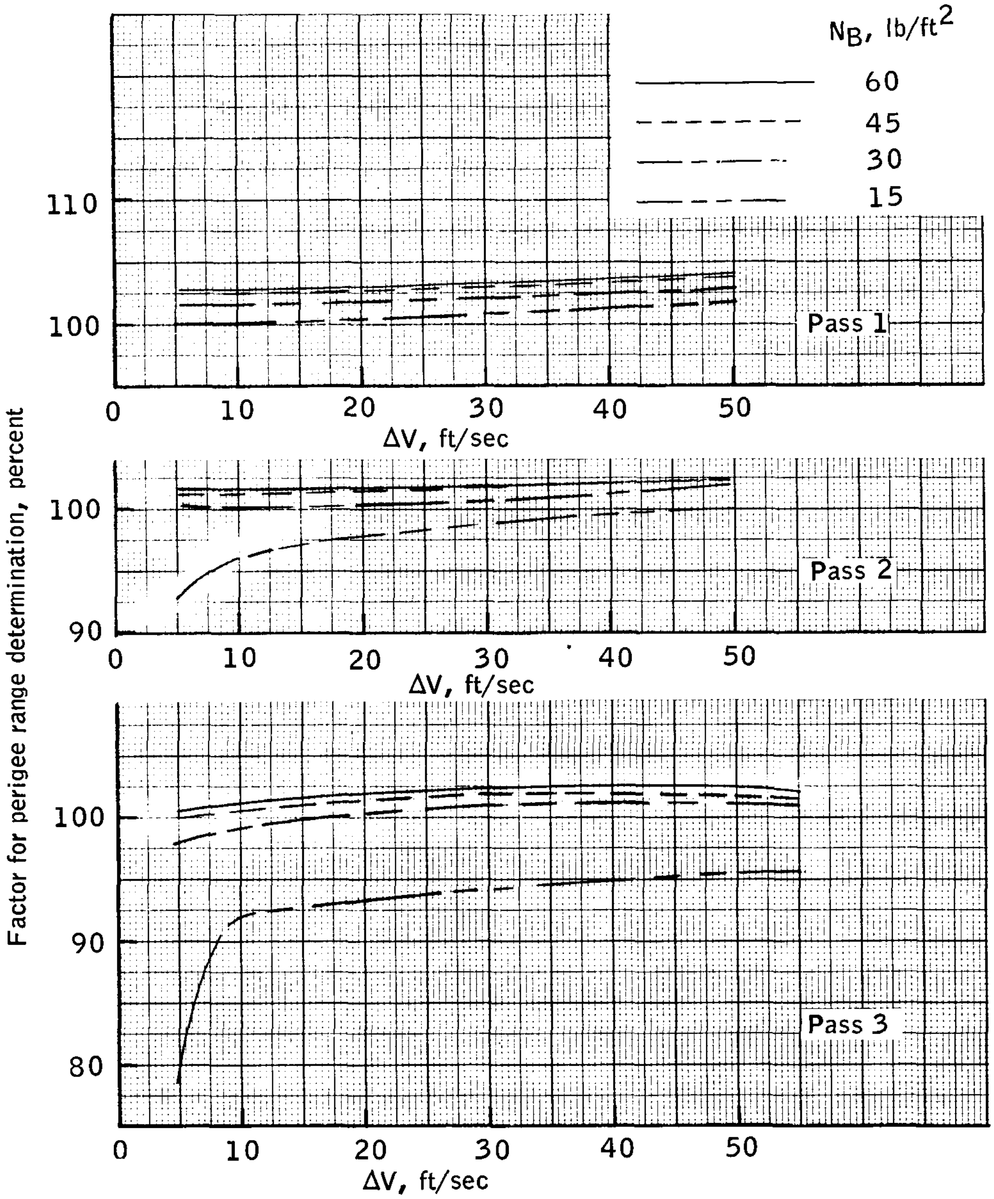

Figure 15. - Factor for perigee range determination as a function of ΔV for specific ballistic numbers and orbital passes.

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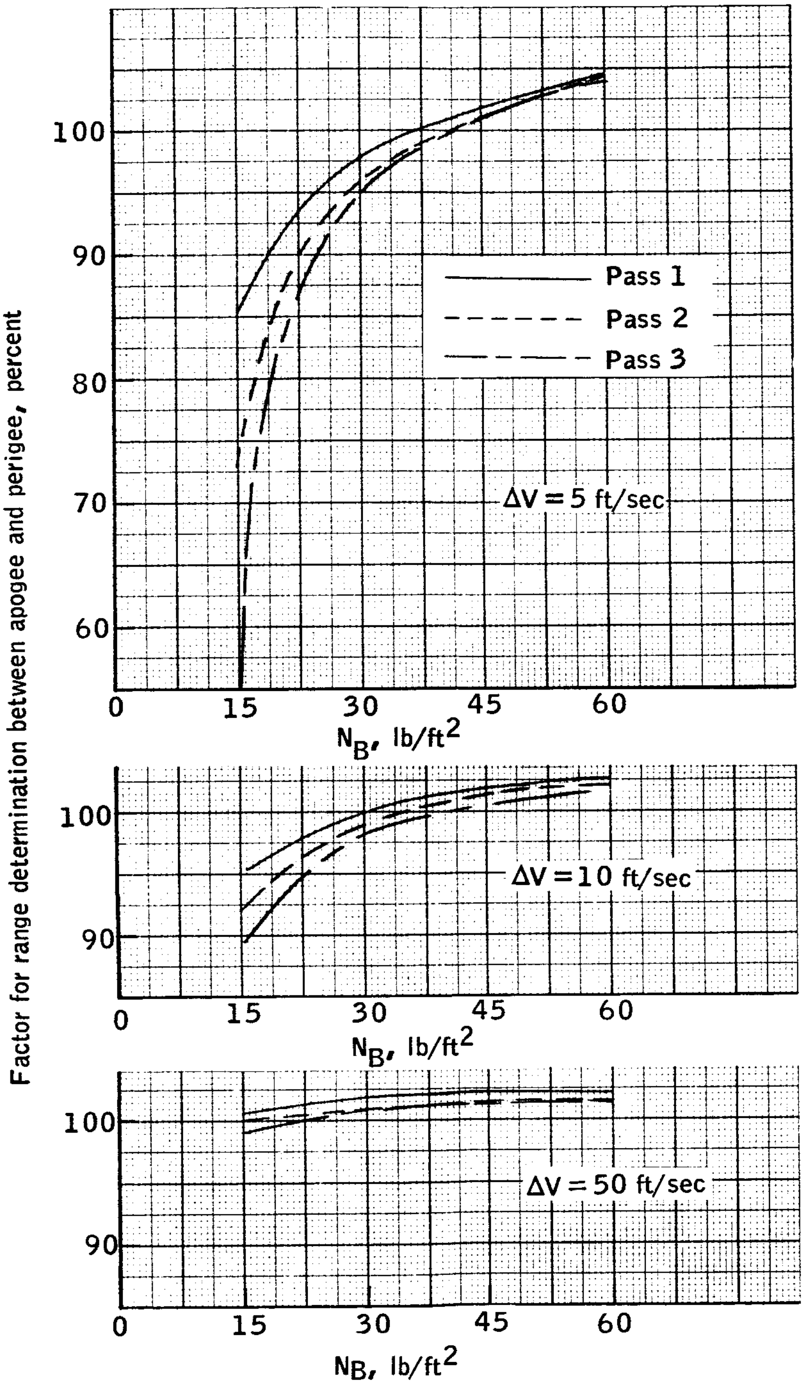

Figure 16. - Factor for range determination between apogee and perigee as a function of ballistic number for specific values of ΔV and orbit passes.

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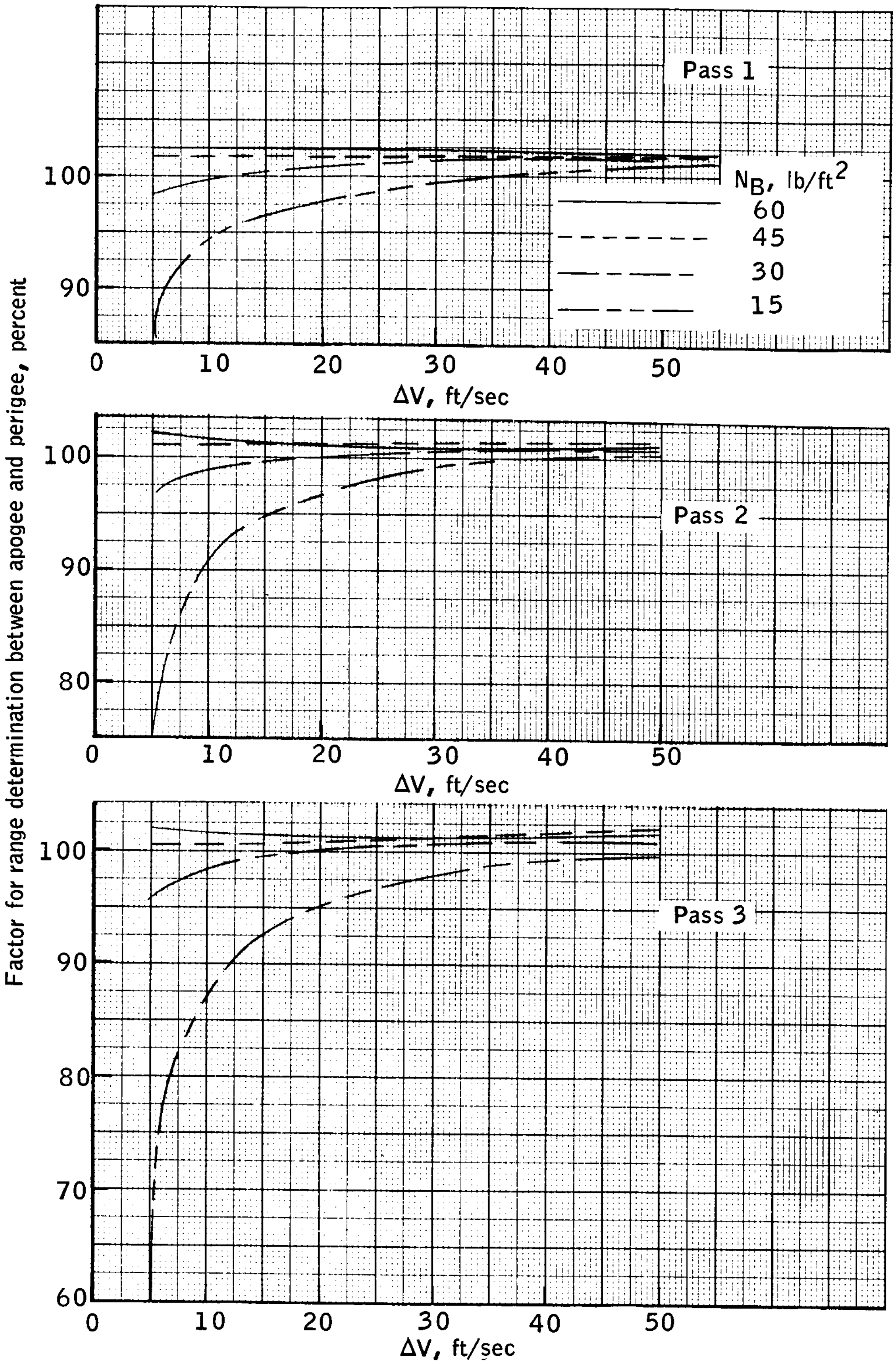

Figure 17. - Factor for range determination between apogee and perigee as a function of ΔV for specific ballistic numbers and orbital passes.

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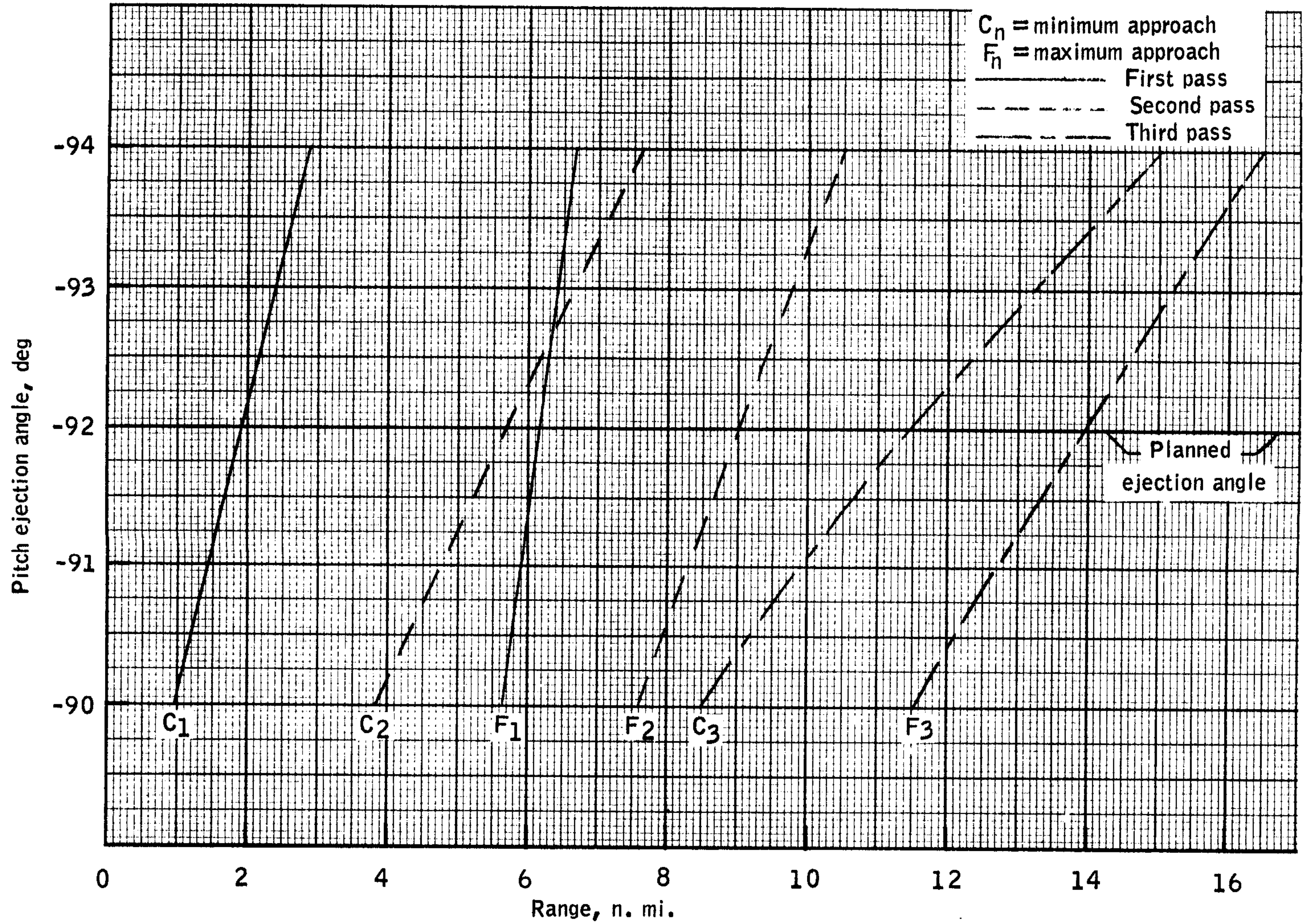

Figure 18. - Ejection angle versus range of minimum and maximum approach for each pass $\Delta V = 10$ ft/sec, $N_B = 28.21$ lb/ft^2.

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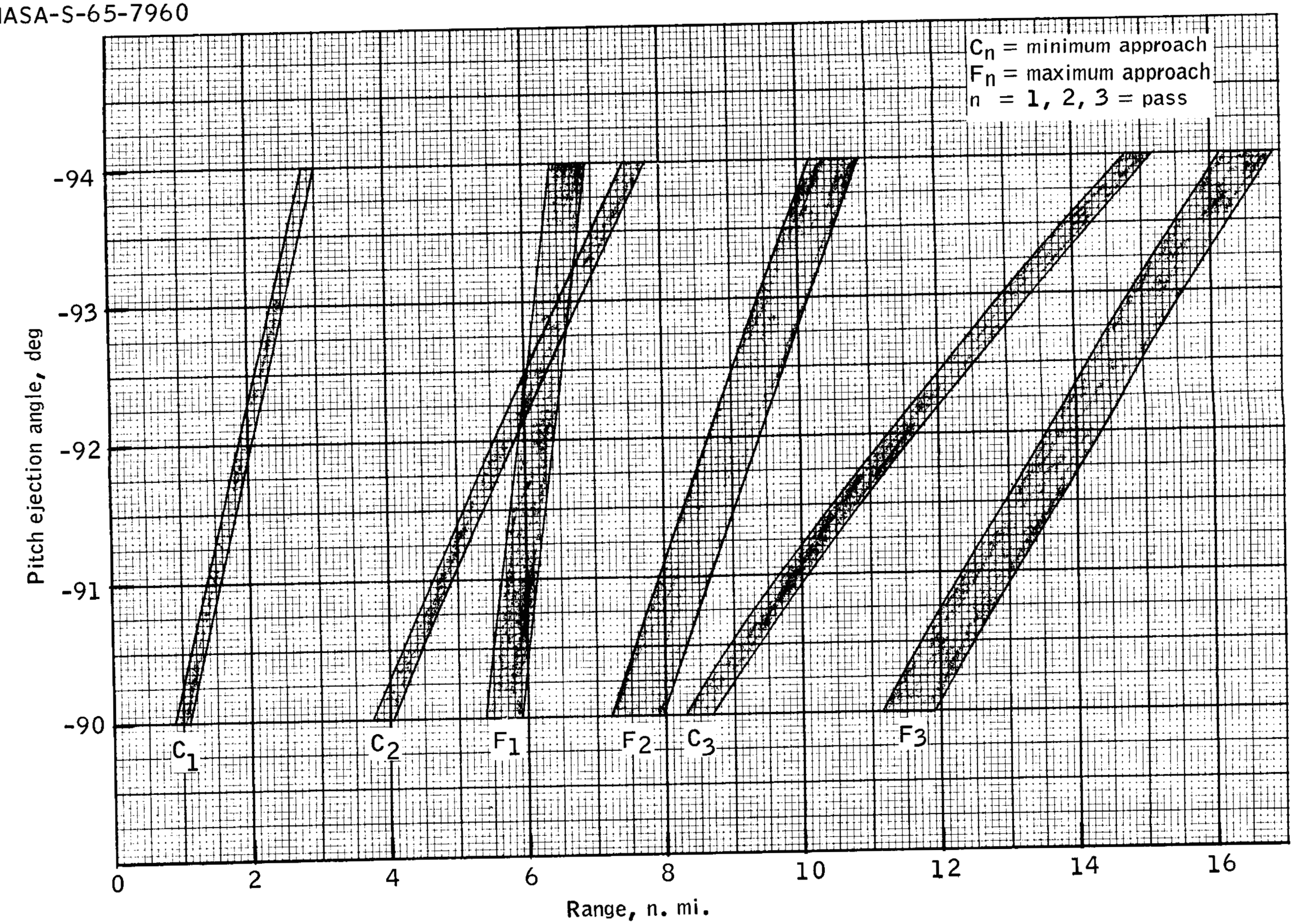

Figure 19. - Ejection angle versus range of minimum and maximum approach for each pass with $\Delta V = 10$ ft/sec $\pm$ 5 percent.

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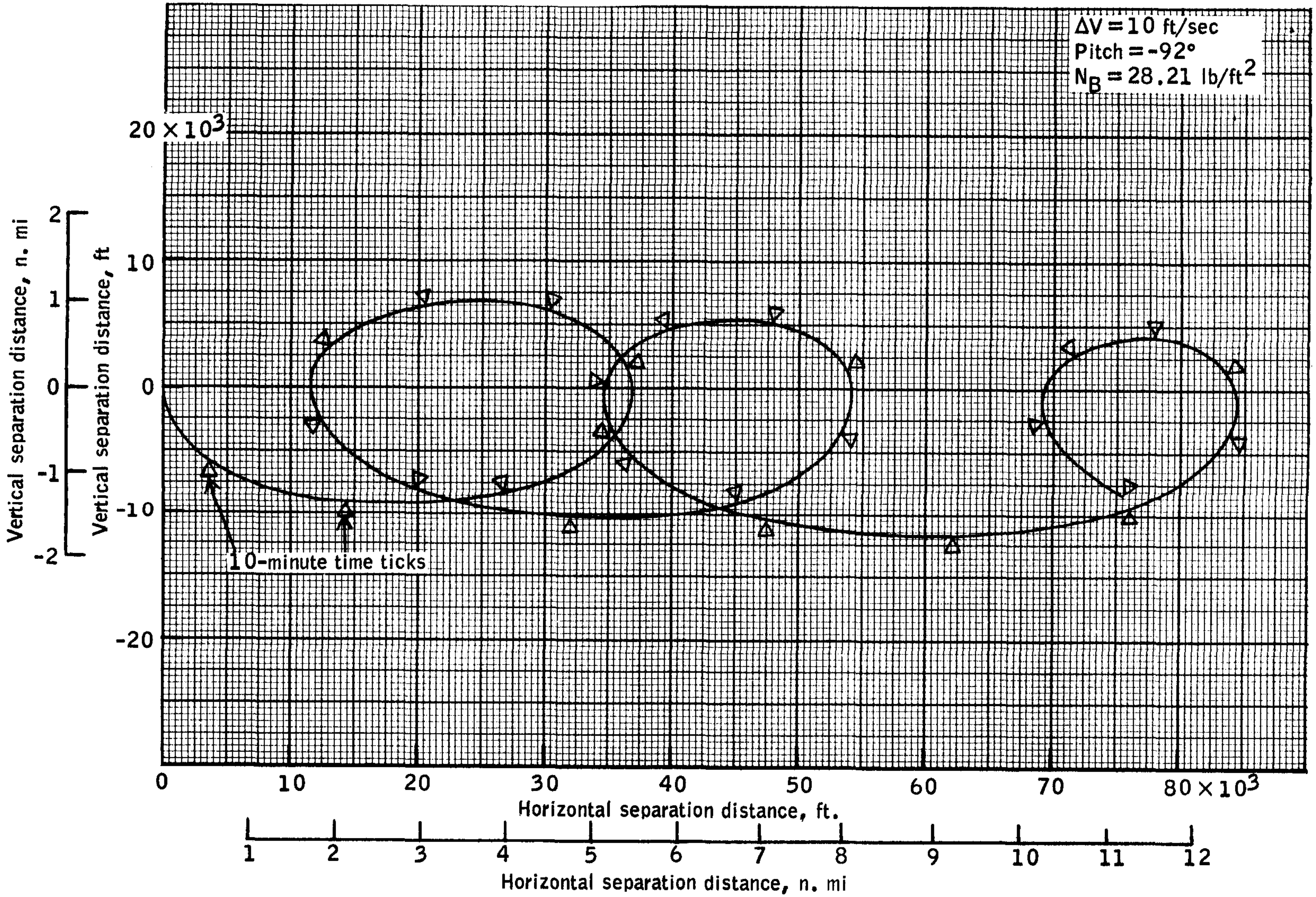

Figure 20. - Vertical and horizontal separation distance.

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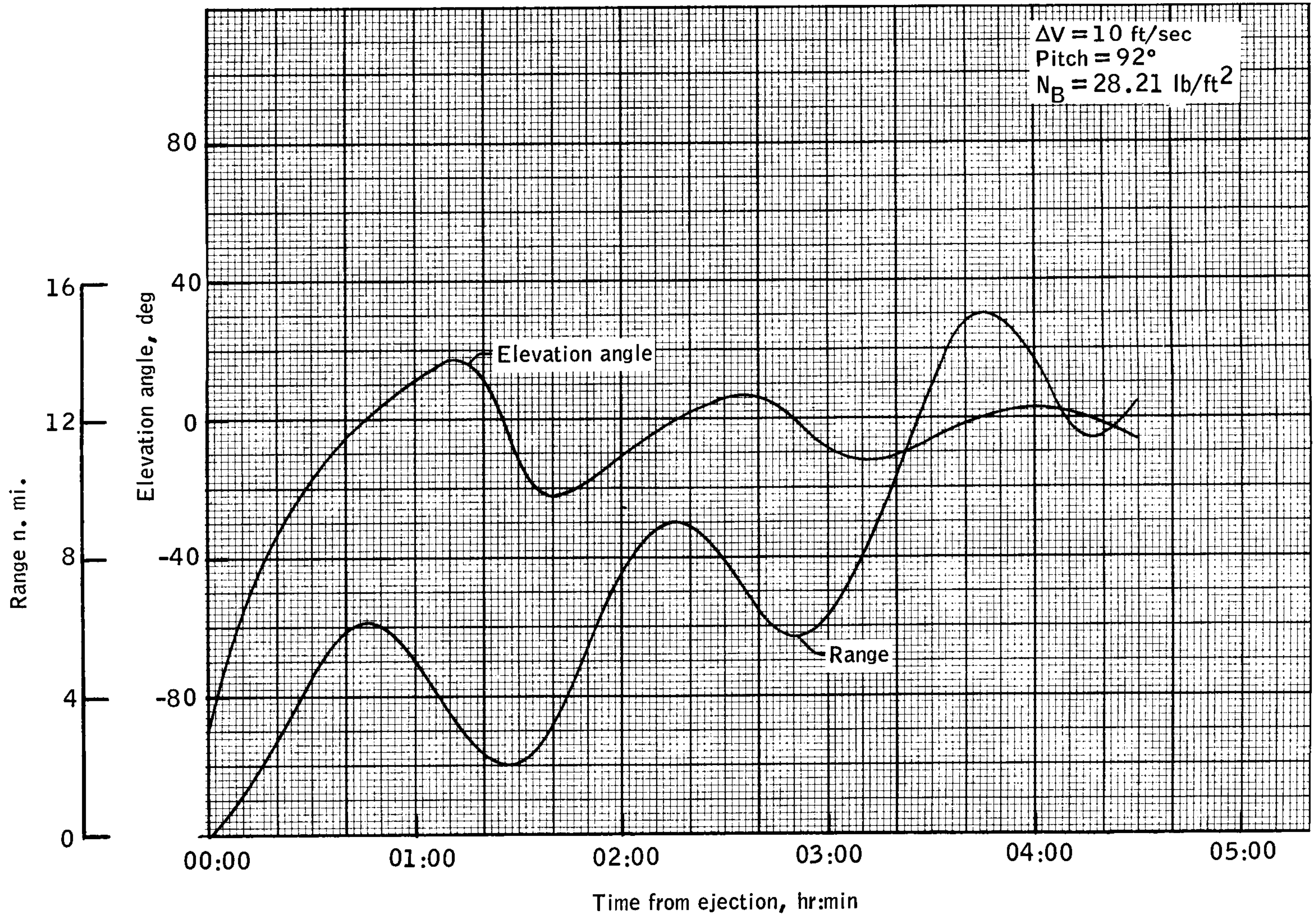

Figure 21. - Elevation angle and range versus time from ejection.